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Column Length Criteria for Resin Bolting in Evaporites

By W. C. Smith and R. M. Stateham



UNITED STATES DEPARTMENT OF THE INTERIOR





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Report of Investigations 9121

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**UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary**

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	min	minute
in	inch	pct	percent
in/in	inch per inch	psi	pound per square inch
lbf	pound force	tons/ft	tons per foot ¹

¹In this report, "ton" indicates 2,000 lbf.

COLUMN LENGTH CRITERIA FOR RESIN BOLTING IN EVAPORITES

By W. C. Smith¹ and R. M. Stateham²

ABSTRACT

This Bureau of Mines report discusses how pull-test data can help establish polyester resin column length criteria for roof bolts in evaporite minerals. The study evaluates the effectiveness of partial to full columns of resin in anchoring 4-ft, No. 6, grade 40 rebar roof bolts in potash, salt, trona, gypsum, and borate mine roofs.

Pull tests were performed on over 600 roof bolts in 11 evaporite mines. Column lengths ranging from 6 to 48 in (fully grouted) were evaluated for each test site. In general, comparative results among all test sites indicate that pull-out loads in excess of 10 tons (force) were attained with resin-grouted bolts having 13 to 75 pct less than a full column of polyester resin. Ten tons (force) of load-carrying capability compared favorably, in terms of strength, with the calculated yield strength of the rebar used in the tests, which was 8.8 tons (force). The site-specific nature of each test site, due to the unique combinations of geology, mine-induced stresses, and other unknown parameters, prevented the establishment of valid generic column-length criteria. For these reasons, data to evaluate resin-column-length effectiveness are best obtained on a mine-specific basis.

¹Mining engineer.

²Supervisory geophysicist.

Denver Research Center, Bureau of Mines, Denver, CO.

INTRODUCTION

This report summarizes a Bureau of Mines investigation concerning column-length effects for untensioned fully grouted resin-anchored bolts in evaporite mines. The objective of the study was to establish minimum effective column lengths for grouted bolts installed in different host minerals. Over 600 resin-grouted bolts were pull-tested in potash, salt, gypsum, trona, and borate.

Bureau researchers have studied the column-length effects of resin-grouted bolts under different mine roof lithologies (4-5, 10, 13, 22).³ Earlier observations indicated that, in general, the load-carrying capability of a fully grouted 4-ft roof bolt exceeded the rated yield strength of the steel rebar. Subsequent Bureau research has investigated the performance of resin-grouted bolts to more completely understand the support mechanisms involved. Some studies have been concerned with applying a design-criteria approach based on minimum bolt performance standards to evaluate the effectiveness of specific grouted bolts installed under in situ conditions.

Efforts have been made in this paper to show how pull-test data can be used to develop column-length criteria for resin-grouted bolts in evaporite roofs. Such information can prove useful when resin losses into fractures and voids cannot be avoided, resulting in less than fully grouted resin columns. Other causes for a shortened column include inadequate installation practices. However, by following the resin manufacturers' directions for resin bolts, these improper installations can be minimized. A special application of this study is in the development of point-anchor resin bolt systems that require less than a full column of grout.

This study is part of the Bureau's program to improve health and safety by reducing the hazards related to roof falls from weak strata in underground evaporite mines. The study was undertaken in conjunction with the evaporite mineral industry, which contributed its mine personnel and equipment to aid in the installation and testing of the resin bolts.

BACKGROUND

Mineable evaporite ore bodies range from a few feet in potash mines to many tens (even hundreds) of feet in salt mines. Two basic mining techniques used to mine evaporite deposits are room-and-pillar and open-stope methods. Room-and-pillar methods are generally used with a continuous cycle of roof bolting, top cutting,

face drilling, blasting, and loading-haulage in most thinly to moderately bedded deposits such as potash, trona, gypsum, and borate. Continuous miners are frequently operated when seam height and orientation are favorable. Room widths range from 14 to 50 ft, with 30 ft as an average. This results in extraction ratios ranging from 60 to 90 pct. The staggered checkerboard pillar system, a commonly used technique, accounts for the highest extraction rate (18).

³Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

In domal and thick-bedded salt deposits, open-stope mining using uniformly spaced pillars is practiced, resulting in 100-ft or more pillar spans. In such massive deposits, multilevel mining is performed in which the pillars on one level are superimposed on those of the next lower level.

As is the case for coal, room widths and pillar sizes in evaporite are dependent on the depth of the deposit, its strength, and the other mechanical properties of the roof and pillar rock that influence the stability of the rock around the mine opening.

Likewise, the roof support requirements for newly mined ground are similar, and the same roof-reinforcement techniques are used in coal.

Resin-grouted bolts, using prepackaged polyester resin systems, show great promise in evaporite mining for four reasons:

1. They can withstand high loads, both horizontal and vertical.
2. They are resistant to corrosion, which is common in saline-bearing minerals.
3. They have high versatility in promoting varying degrees of beam building and suspension, depending on the hole depth and length of grout column.

4. Passive support systems exert no or little active force on the formation (important because of the high creep behavior of some evaporites and shales when subjected to loading).

Resin loss into voids and fractures in the surrounding rock is a serious problem when installing fully grouted bolts in relatively weak roof strata, such as those composing many evaporite roofs. Often the only indication for a fully grouted hole is the extrusion of resin around the hole collar as the rebar is pushed in. The prevalent use of steel bearing plates can hinder this inspection process because the placement of the plate over the hole conceals the visible evidence of the length of grout column.

This degree of uncertainty from bolt to bolt necessitates the establishment of an inspection technique to evaluate the integrity of the grout column in place. The pull test is, at present, the most direct way to study bolt integrity in resin-grouted bolts. The column length effects studied in this investigation were primarily obtained from pull-test data on resin-grouted bolts with known installed column lengths.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the cooperation and assistance given by the management and personnel of Tenneco, Inc., Processing and Marketing Minerals Dept.; Stauffer Chemical Co. of Wyoming; Georgia Pacific Corp., Blue Rapids Mine and Mill; U.S. Gypsum Corp.; Duval Corp.; Amax Chemical Corp.; Kerr McGee Corp., Mineral Exploration Div.; Morton Salt Co.; International Salt Co.; American Borate Co.; and U.S. Borax and Chemical

Corp. for their cooperation in the data collection; their contributions in personnel and equipment made possible the installations at the test sites and the testing of the resin-grouted bolts. Acknowledgment is also given to W. W. Watts, former Bureau of Mines Principal Investigator on this project, for conducting field investigations and collecting data during the project's initial stages.

SITE PREPARATION AND INSTRUMENTATION PLAN

To meet the objectives of the study, 11 suitable mine sites were selected in 5 minerals: potash, salt, gypsum, trona, and borate (fig. 1). At each site, 60 to 80 resin-grouted bolts of variable column lengths were installed and pull-tested to evaluate anchorage capacities in the various minerals. The installation of fully grouted bolts was accomplished by drilling 4-ft-long, 1.0- to 1.2-in-diam boreholes; the correct length of pre-packaged resin was inserted into each borehole to completely fill the annulus between the hole and the rebar. Partial resin columns were created by reducing the length of the resin cartridges that were inserted into the boreholes; when possible, predetermined column lengths ranging from 6 to 48 in were established for all of the test sites. All installation procedures followed resin manufacturers' instructions. Visual inspections with the fiberoptic borescope (9) were routinely conducted to ensure that the boreholes did not contain open fracturing. To check for adequate grout column

after bolt installation, boltheads were cut on selected bolts and a wire was inserted to gauge the depth of open hole near the collar. At some test sites, entire column lengths were omitted when the respective bolts did not meet the suitability requirements for proper installation.

The bolts consisted of 4-ft-long, 0.75-in-diam, No. 6 type, grade 40 steel rebar; 0.88-in-diam, No. 7 type, grade 40 steel rebar was used exclusively at one borate test site. (Steel quality is designated according to the ASTM Standard Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement.) Generally the bolts were installed in a grid pattern on 2.5- to 3-ft centers. A 6-in-square bearing plate and pull collar were slipped over each bolt head prior to installation to allow the use of the pull-testing apparatus (fig. 2). The pull-test equipment consists of a hydraulic piston assembly, an extensometer, and a dial gauge to measure bolthead displacement (fig. 3).

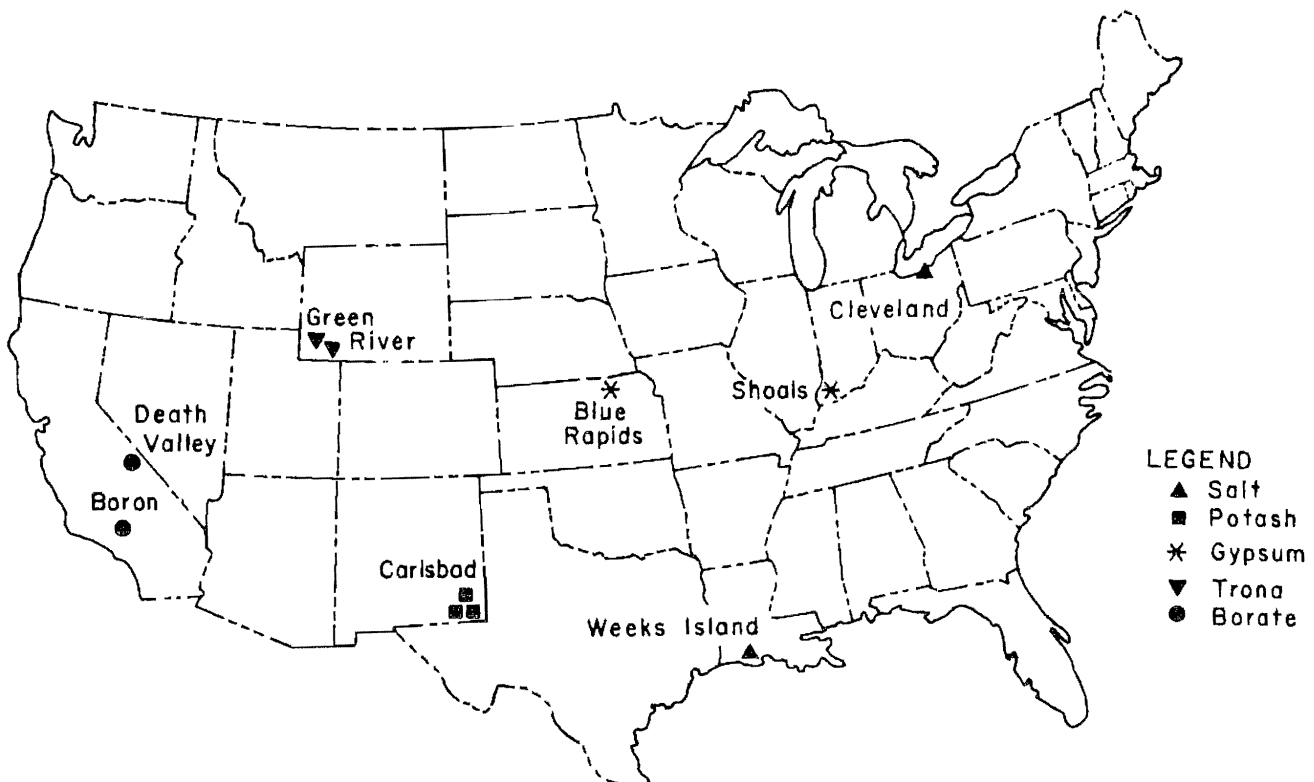


FIGURE 1.—Locations of mine sites used in study.

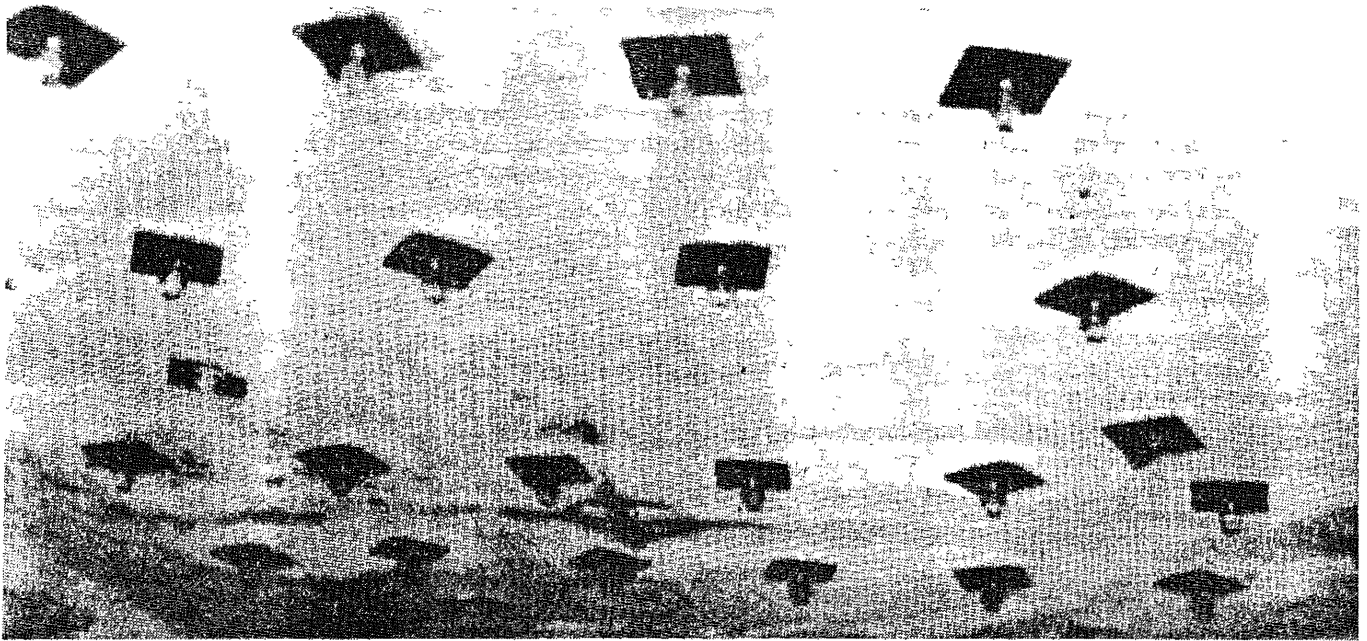


FIGURE 2.—Typical test site showing bolt layout.

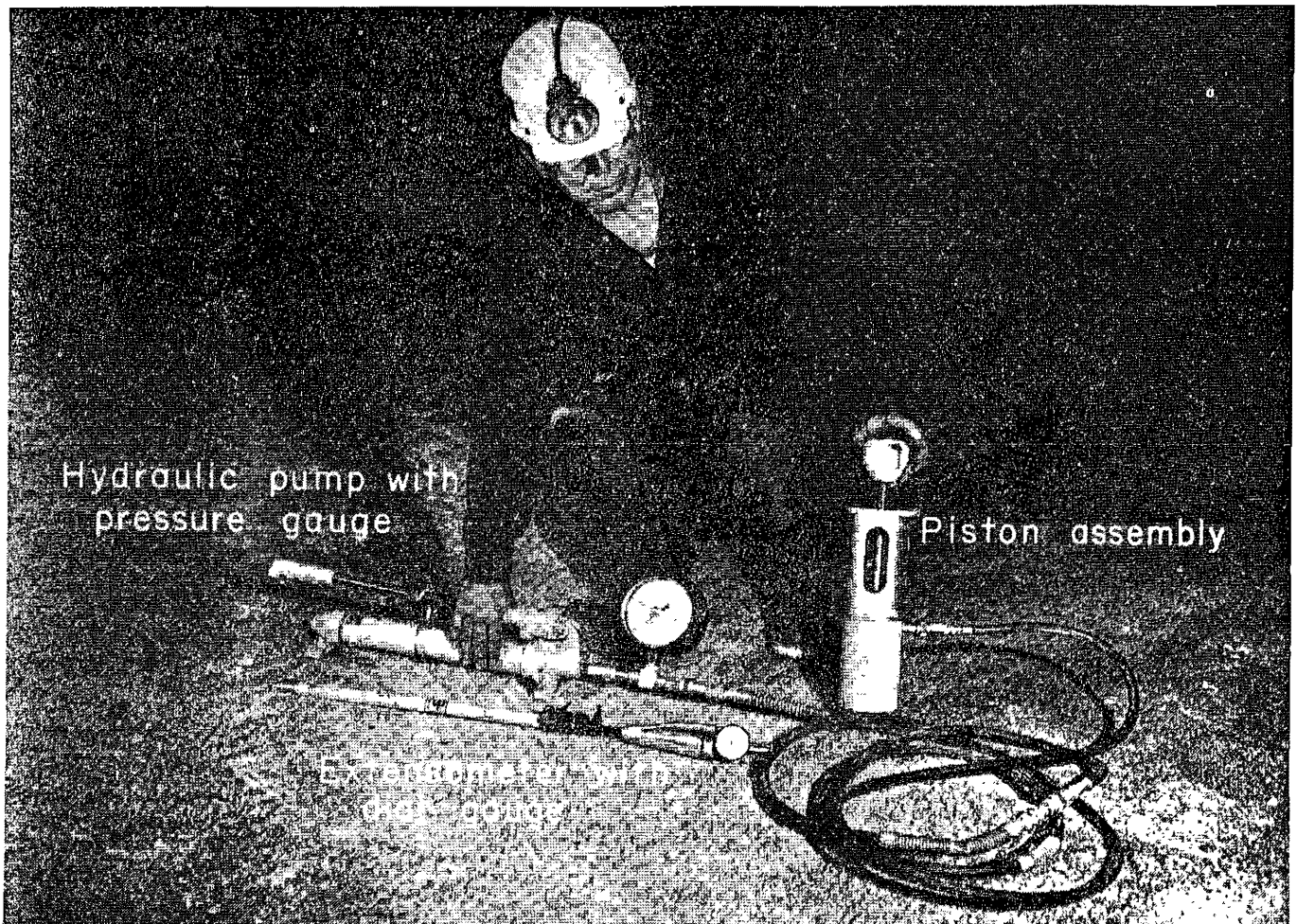


FIGURE 3.—Pull-test equipment.

TEST PROCEDURE

The roof bolt pull-test procedure was designed to measure the short-term ability of the bolt to resist an applied load under in situ conditions (17). That strength is determined by a pull test in which the bolthead displacement is measured as a function of the applied axial load. The accuracy of the instrumentation is ± 0.001 in and ± 100 lbf. For the field tests, loading was increased in 1,000-lbf increments with the accompanying displacement recorded at each increment up to bolt failure. The same pull-test equipment was used in all of the tests. Figure 4 shows a pull test in progress.

Special efforts were made to install the resin bolts in roof rock typical of the various mineral deposits. For instance in potash mines, test sites were selected based on the availability of sufficient thicknesses of potash (low grade) in the roof to allow pull testing solely within that mineral. In this way the pull-test data could be compared from mineral to mineral and mine to mine.

When possible, pull testing was performed on 4-ft bolts in holes of similar length with 48-, 42-, 36-, 30-, 24-, 18-, 12-, and 6-in resin columns. Installation difficulties at both borate mines prevented the testing of some column lengths, although sufficient data were obtained for comparative purposes. Figure 5 shows how fractures can influence column lengths.

To properly account for steel elongation in the bolt, a correction factor is sometimes used to determine the actual displacement along the grouted portion. The factor assigns a different elongation constant for the grouted and the ungrouted sections; calculated elongation for ungrouted 0.75-in-diam, type 40 steel is 0.000075 in/in per 1,000 lbf of load. In practice, when applied to this study,

the corrected values often registered negative deformations, i.e., apparent shortening of the bolts under mild loads, 2 to 3 tons.⁴ This improbable effect was largely attributed to overcorrection and exemplifies an error in the assumptions for steel behavior due to loading



FIGURE 4.—Pull test in progress showing resin bolt undergoing loading in 0.5-ton (force) increments.

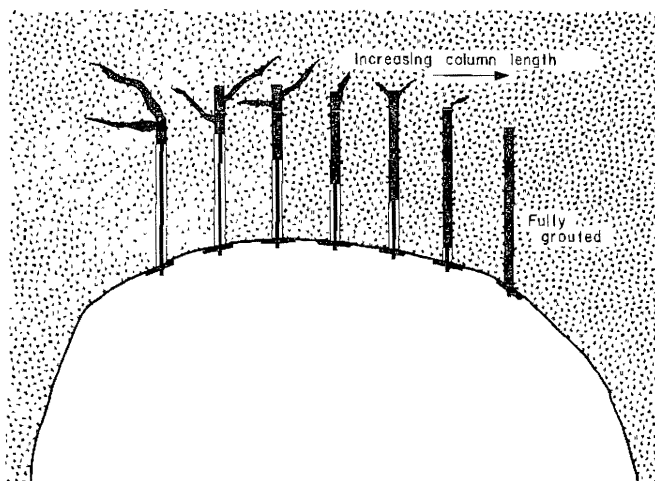


FIGURE 5.—Cross section of mine opening showing different grout column lengths with resin migration into open fractures.

⁴In this report, "ton" indicates 2,000 lbf.

conditions. Because the calculated steel stretch amounted to less than 10 pct of the total displacement at loads less than the elastic limit of the rebar and since the true steel elongation was not accurately determined, uncorrected data are presented in this paper. In practice,

the total displacement at the bolthead is more important in terms of mine roof safety since it more closely reflects the actual downward movement at the roof line. The procedure additionally assured more overall consistency in the results and added conservatism.

TEST STANDARD FOR THE EVALUATION OF PULL-TEST DATA

To properly evaluate the pull-test data for this project, a criterion for judging single bolts was instituted that applies specific guidelines to bolt displacement and load values. These guidelines represent a method whereby acceptable bolts can be separated from unacceptable bolts based upon their respective load-displacement behaviors.

The method used to evaluate the grouted bolts follows:

1. Load-displacement curves were plotted from field data, and the yield point was chosen for every pull test. The yield point is defined here as the initial point of departure from linearity on the load-displacement curve (fig. 6).

2. A pass-fail criterion was applied to each load-displacement curve to evaluate whether minimum requirements

identifying an adequately installed bolt were met. The requirements specify a load that equals or exceeds the calculated yield strength of the No. 6 grade 40 rebar (8.8 tons) with no more than 0.2 in of displacement (fig. 6). The 0.2 in of displacement was arbitrarily chosen as a reasonable maximum allowable displacement. The bolts were grouped according to column length.

3. By grouping bolts according to column length, determinations were made concerning the overall success of particular column lengths for all test sites. An adequate sample size of six or more bolts was defined for this study under acceptable statistical methods, such as the Chi-square goodness-of-fit test. The percentages of "passing bolts" were calculated for all column lengths in each site. The shortest column length at which at least 90 pct (arbitrarily assigned) of the bolts within that group met or exceeded the requirement for acceptable bolts in terms of load-carrying capability is identified in this investigation as the effective column length (ECL). A more detailed presentation of the data is provided in appendix A. An ECL was determined for every mine. For ease of presentation, figures A-1 to A-5 show average load-displacement results for each column length; figures A-6 to A-10 show the percent of "passing bolts" for each test site. For the ECL determinations, bolts were evaluated individually under steps 2 and 3. Attempts to determine the ECL directly from these figures will give slightly different results from those presented.

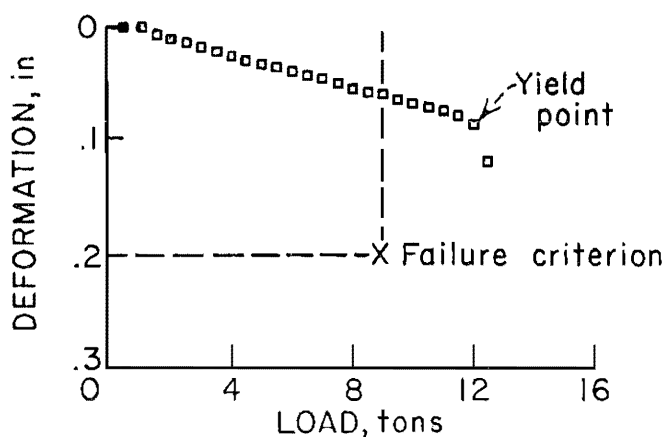


FIGURE 6.—Load-displacement curve for a roof bolt that exceeds the failure criterion of 8.8 tons (force), 0.2 in.

TEST SITE BACKGROUND

GROUND CHARACTERIZATION OF EVAPORITES

A brief geological background of the study sites is presented for the reader's information. Additional information on the test sites is included in appendix B.

Evaporites are mineral deposits formed by the precipitation of mineral salts in restricted water bodies such as inland seas, lagoons, and terrestrial playa lakes, and in effluent from mineralized springs. The precipitation of evaporites from brines is governed chiefly by the different solubilities of the individual salts and by the temperature and overall composition of the brinewaters. The order of deposition in evaporite beds usually consists of repetitive sequences of limestone, gypsum, anhydrite, and borate; salt (halite) and potash; or trona and salt. Mudstones, shales, and clays, which represent major changes in the depositional environments, often separate repetitive evaporite sequences. Such interruptions in the sequences can lead to potential weakness planes in underground mine roofs (figs. 7-8).

Other causes for structural weaknesses are the effects of tectonic forces, which can contribute to high in situ horizontal and overburden pressures, causing micro-faulting, brecciation, fracturing, and convoluted bedding (16). Figure 9 shows fracturing in an evaporite mine roof. Several borate seams in southeastern California exhibit similar structuring. Salt domes that lie along the U.S. gulf coast are the product of bedded salt deposits squeezed by high overburden

pressure into mushroom-like shapes; the intense loading can frequently result in brittle and slabbed zones within the salt structure (2).

PHYSICAL PROPERTIES OF EVAPORITES

Physical properties testing was performed on potash, salt, gypsum, and trona using NX-diameter cores with a 2:1 length-to-diameter ratio. Rock samples from each field test site were obtained for laboratory testing. The tests involved using standard triaxial testing procedures to determine the uniaxial compressive strength, shear strength, angle of friction, Young's modulus, and Poisson's ratio. The results of the tests are included in table 1.

The purpose of the laboratory investigation was to obtain short-term physical properties to conform with the time duration of the standard pull test, 5 to 10 min. Longer term creep studies were not deemed appropriate for this type of research.

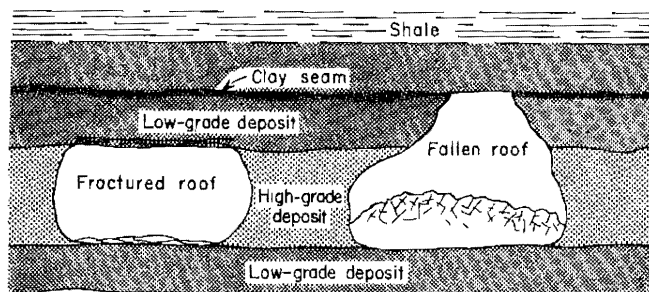


FIGURE 7.—Ground control problems encountered in bedded evaporites (modified after Serata, 21).

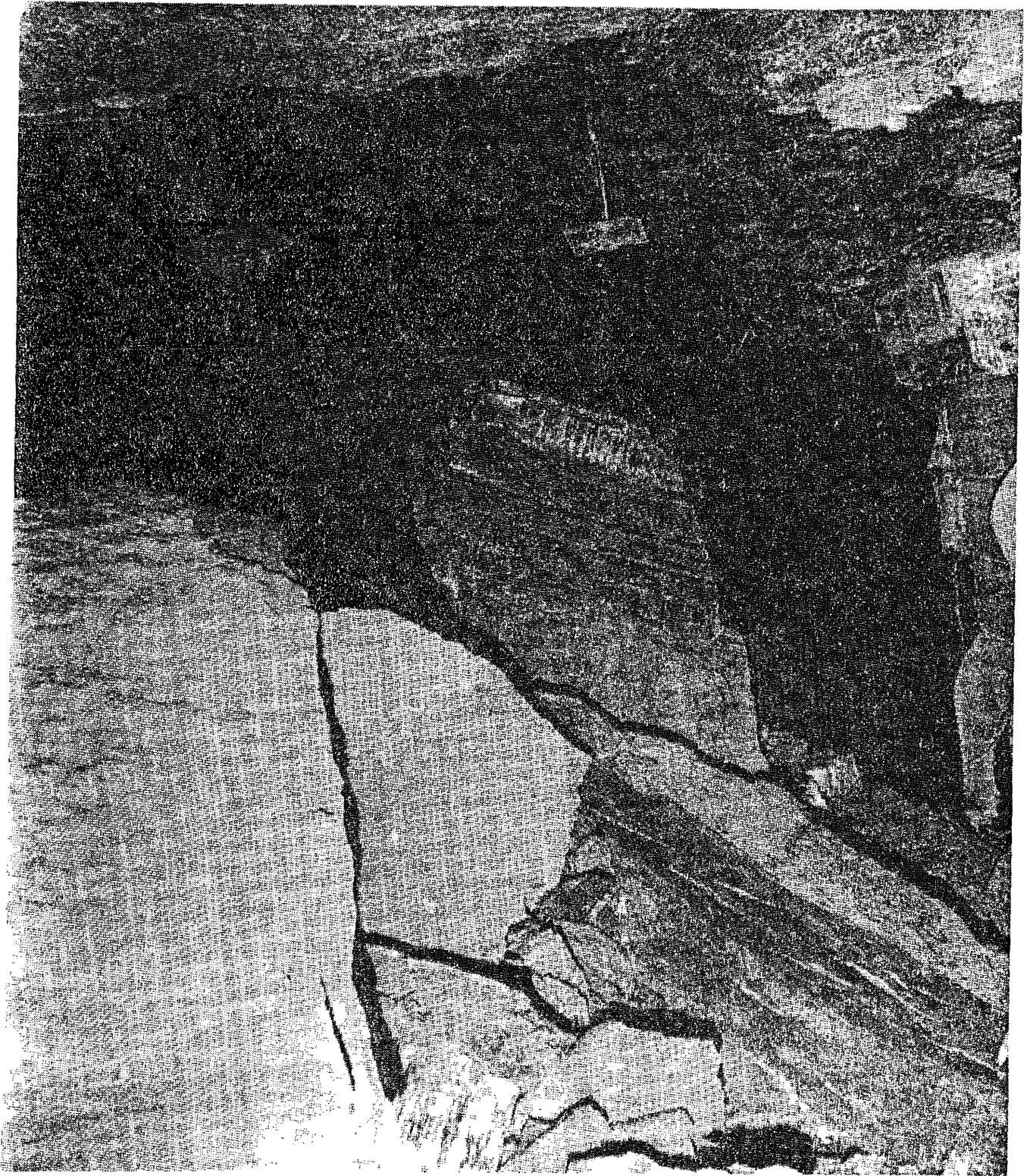


FIGURE 8.—Roof fall in bedded evaporite.

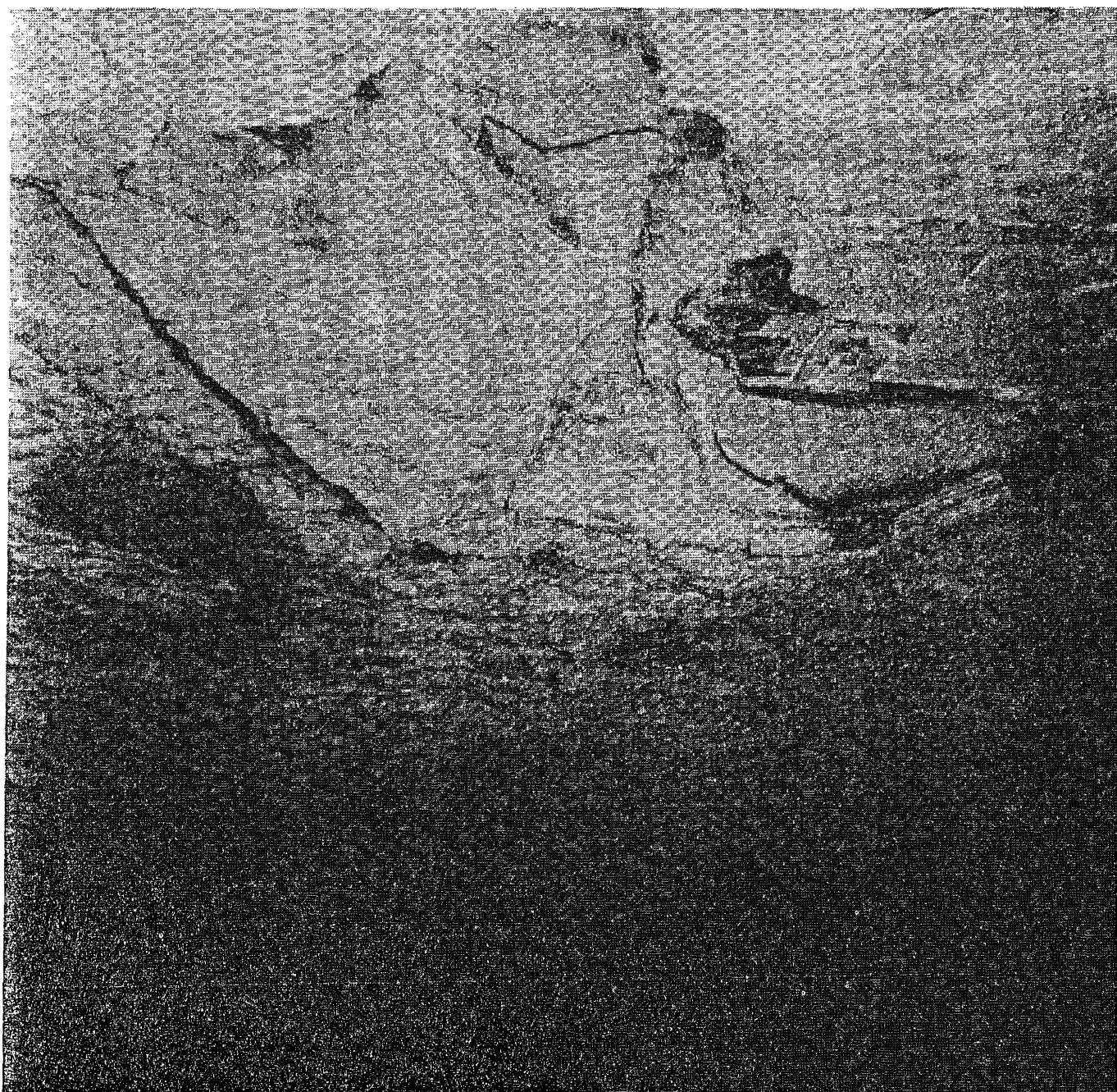


FIGURE 9.—Fractures in mine roof.

TABLE 1. - Physical properties of tested evaporites

Sample type and source	Uniaxial compressive strength, psi	Shear strength, psi	Internal angle of friction, °	Young's modulus, 10 ⁶ psi	Poisson's ratio ¹
Potash:					
Mine 1.....	3,689	886	40	1.12	0.20
Mine 2.....	3,321	680	47	1.32	.16
Mine 3.....	4,244	1,108	35	1.82	.35
Salt:					
Mine 1.....	2,754	1,001	29	.52	.31
Mine 2.....	3,625	1,488	17	1.32	.34
Gypsum:					
Mine 1.....	3,131	1,022	26	1.82	.21
Mine 2.....	2,975	1,004	24	.60	.20
Trona:					
Mine 1.....	4,270	811	51	1.17	.16
Mine 2.....	6,650	1,312	33	1.15	.17

¹Estimated at 50 pct of ultimate load using conventional laboratory testing procedures.

NOTE.--Borate not included because samples were highly fractured, preventing proper preparation and testing.

RESULTS

PULL-TEST DATA

The pull-test data suggest that loads in excess of 12 tons are attainable with resin-grouted bolts installed in evaporite mine roofs. This compares favorably, in terms of strength, with the calculated yield load of 8.8 tons for grade 40 steel; reasons for the discrepancy are addressed later in the paper. These results show that 4-ft-long, fully grouted, No. 6 type, grade 40 rated steel bolts provided sufficient load-carrying capacities at all but one of the test sites.

Under incompetent roof conditions, longer and/or larger diameter steel rebar may be needed to ensure adequate support. Such a roof condition was experienced in one of the borate mine test sites in which fully grouted, No. 7 (7/8-in-diam), grade 40 rated steel was used. The reason for using the No. 7 rebar at this particular mine was the difficulty encountered in drilling the necessary 1-in-diam hole for installing No. 6 rebar as was originally planned. The fully grouted resin bolts with No. 7 rebar were pull-tested to an average of 13.5 tons. The data for the No. 7 rebar at that borate mine were not intended as a direct

comparison to the data from the other borate mine using No. 6 rebar, since both kinds of rebar have varied yield strengths and anchorage areas. Instead, the data suggest that even under a weak roof, an acceptable level of support can be established with resin-grouted bolts.

The ECL method, as used here, not only evaluates the short-term bolt load but also places a limit on the tolerable displacement at yield allowed in the roof bolt-resin-rock system. An inherent assumption in this technique is that the ability of a bolt to sustain high loads is deemed unacceptable if the corresponding bolthead displacement is high (greater than 0.2 in).

The ECL was determined for all of the mines studied. A statistical interpretation of the results indicates a high scatter between mineral type and the ECL column (fig. 10). A similar lack of relationship exists ($r^2 = 0.34$) between the physical properties of the minerals and the ECL (fig. 11).

An evaluation of the column length data for the test sites suggests that the ECL method can provide sound results when applied to evaporite minerals if used solely as an index parameter of bolt

anchorage effects. The results of the evaluation are included in table 2. The average ECL for the study is 26 in. While individual column lengths within mineral groups can vary dramatically, such as 12, 30 and 36 in in potash, averages for each evaporite type show closer similarities within a mineral group. (The range is ± 4 in.) Average ECL by mineral group is as follows: salt, 24 in; gypsum, 24 in; potash, 26 in; trona, 30 in; and borate, 42 in, or nearly a full-grout column. Nevertheless, it should be emphasized that because of the variability of geology, stress conditions, etc., from one mine to another, ECL determinations are still best obtained on a mine-specific basis. This has been shown by the data in this investigation.

For the study using No. 6, type 40 rebar, the average maximum pull-test load at the ECL (26 in) compared to 95 pct of the average maximum pull-test load at 48 in of grout column (table 2). The reader is reminded that at column lengths beyond the ECL, the actual grout to rock anchorage exceeded the yield strength of the steel rebar. Otherwise, failure of the rebar would not have occurred under the loading conditions of the pull test. In this investigation, mention of bolt anchorage refers to the failure load measured as a result of the standard pull test, not the actual rock-grout anchorage.

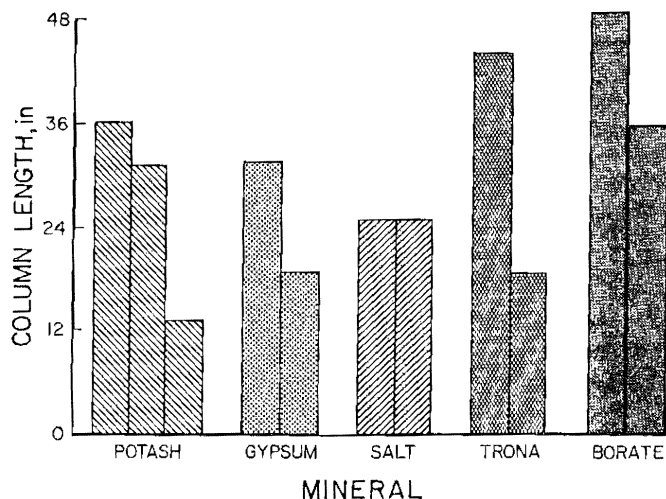


FIGURE 10.—Effective column length determinations. Each bar represents a study site.

The type 40 rated steel rebar functioned in accordance with ASTM standards, which required that the steel bolts tested exceed their minimum rated yield specifications. On average the type 40 steel rebar used in the study exceeded the yield specifications (40,000 psi) by approximately 14,000 psi. The literature indicates that upon the failure of the steel-grout interface, the rebar contracts near the bolt head, allowing for tensile failure in the steel regardless of grout or rock properties (3, 6). In effect, steel behavior overwhelmingly dictates the bolt behavior beyond the critical column length (ECL). Beyond the ECL the resin-rock anchorage exceeds the bolt strength and is no longer measurable using conventional pull-test procedures.

RESIN PERFORMANCE AND UNIT ANCHORAGE

Another vital consideration regarding rock-to-resin bonding is resin performance. As previously discussed, the roof bolt pull test measures bolt anchorage under an axial load and is often used as

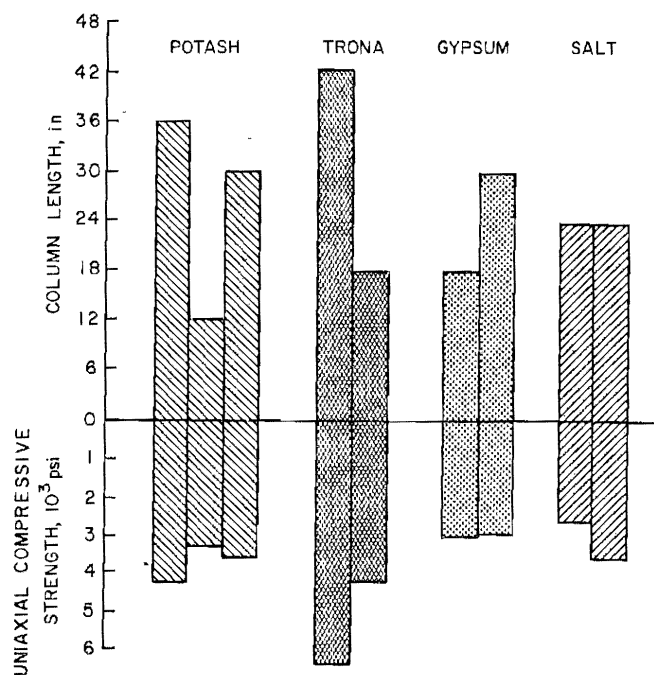


FIGURE 11.—Relationship between effective column length and compressive strength of roof rock. Each bar, above and below the horizontal axis, represents a study site.

TABLE 2. - Effective column lengths showing anchorage comparisons with fully grouted bolts

Sample type and source	Effective column length, in ¹	Anchorage at effective column length, tons	Full-grout anchorage, pct	Unit anchorage, tons/ft
Potash:				
Mine 1.....	36	12.8	100	4.3
Mine 2.....	12	12.0	87	12.0
Mine 3.....	30	13.2	98	5.3
Salt:				
Mine 1.....	24	11.2	96	5.6
Mine 2.....	24	11.5	92	5.7
Gypsum:				
Mine 1.....	18	10.9	95	7.4
Mine 2.....	30	11.8	94	4.4
Trona:				
Mine 1.....	42	12.5	92	3.6
Mine 2.....	18	12.7	100	8.5
Average.....	26	12.1	95	6.3
Standard deviation...	9.5	.78	3.9	2.63

¹Using 8.8-ton, 0.2-in criterion.

NOTE.--Borate not included owing to insufficient data.

a check for proper bolt installation. In fact, field work at one borate mine showed that installing fully grouted bolts does not always ensure a full column of hardened resin. Causes for such an occurrence can be boreholes that are not adequately dimensioned and/or improper bolt spin time and thrust (4, 10). In other cases, enough column bonded to the rock, often near the collar, to turn a seemingly ineffective installation into one that satisfied the load-displacement characteristics deemed necessary in this investigation for proper support (assuming that the bolt holds the roof in suspension, concentrating the load near the collar).

The assumption for unit anchorage of uniform or near-uniform loading distributions along the entire column length becomes inappropriate when substantial zones of unmixed resin-catalyst occupy the borehole with mixed grout. The problem increases in complexity when the relative positions of the hardened and unhardened resin are not identified. Under these conditions, particularly with the longer columns, the term "unit anchorage" is inappropriate. The pertinence of this

phenomenon to this investigation is not fully known because of the many geological and equipment operational variables that occur differently under actual field conditions from site to site. This problem can become more critical under actual mining conditions, where less attention is given to bolt installation procedures and equipment operation, than in more controlled testing conditions such as those practiced in this study. Similarly, less attention is given to changes in geologic conditions than is possible in more controlled field testing situations. By carefully following the resin manufacturers' recommendations for proper bolt installation, effects detrimental to a sufficient grout bond were minimized for this study.

It should be realized that the roof bolt pass-fail criterion was used in this investigation, solely to determine the relative effectiveness of specific column lengths without regard to the actual condition or position of the cured grout except in respect to its ability to resist the tested loads. By carefully installing the resin bolts in a manner consistent with resin manufacturers'

recommendations, a competent installation was assumed.

An evaluation of the overall data reveals high variability in the unit anchorage at the lesser column lengths (less than 24 in). Standard deviations of almost 36 pct were reported at 12 in of grout, which finally stabilizes to 3 pct at 30 in of column. The drop, illustrated in figure 12, is largely attributed to progressive steel failure, which restricts the ability of the roof bolt to carry increasing loads.

In effect, the load values at bolt yield become more similar as the full grout column is attained, reflecting the consistent bolt-to-bolt steel properties, which eventually supersede any actual differences in pullout strength. This effect negates the usefulness of unit anchorage at the upper column lengths.

The concept of unit anchorage becomes highly suspect in cases where a significant portion of the "total anchorage" is due primarily to bolt yielding instead of actual rock-to-resin anchorage. In the true sense of the word, for a given grout length past the ECL, the unit anchorage is unknown since the bolt failure inhibits the measurement of the true anchorage at that column length. The assumption of a nearly uniform stress distribution at the grout-rock interface (necessary when determining unit anchorage) is valid for

loading conditions in which the elastic limit of the rebar is not exceeded (3, 6). In this case, the strength of the rock-grout bond determines the breaking load (anchorage). To study bolt behavior without steel effects influencing the resultant behavior, 12-in columns were evaluated in this investigation.

An examination of the pull-test loads for all 12-in columns demonstrated contrasting rock-resin bond performances that may be as much a consequence of the physical characteristics of the borehole wall as of the mineral type. Wide disparities in unit anchorage were found within mineral groups: potash, 6.4 to 12 tons/ft; salt, 4.5 to 6.2 tons/ft; trona, 7.5 to 8.3 tons/ft; and gypsum, 3.2 to 8.0 tons/ft (table 3).

The wide ranges in unit anchorages illustrate the requirement for a more site-specific approach to roof support needs, in order to address varied conditions peculiar to certain mine conditions. For instance, hole complexities such as roughness, changes in diameter, varying degrees of fracturing, and the presence

TABLE 3. - Twelve-inch column lengths showing anchorage comparisons with fully grouted bolts

Sample type and source	Anchor-age, tons	Full-grout anchor-age, pct	Unit anchor-age, tons/ft
Potash:			
Mine 1.....	6.4	47	6.4
Mine 2.....	12.0	87	12.0
Mine 3.....	7.0	58	7.0
Salt:			
Mine 1.....	6.2	53	6.2
Mine 2.....	4.5	36	4.5
Gypsum:			
Mine 1.....	8.0	70	8.0
Mine 2.....	3.2	25	3.2
Trona:			
Mine 1.....	7.5	55	7.5
Mine 2.....	8.3	172	8.3
Average.....	7.0	56	7.0
Standard deviation..	2.49	18.9	2.49

NOTE.--Borate not included owing to insufficient data.

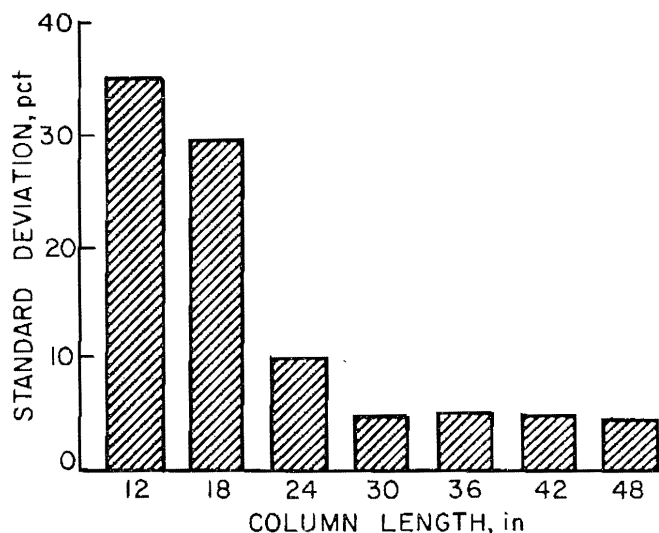


FIGURE 12.—Standard deviations of unit anchorages computed for all bolts used in study.

or absence of voids can significantly alter the degree of resin-to-rock anchorage (19-20, 23). The exact interactions of such parameters at the specific test sites for this investigation are not known. Their characterization is strictly observational, as this was considered the appropriate approach within the scope of the project objectives.

Inspection of samples from several mines revealed the presence of multiple bed partings, often containing clay seams and discontinuities such as fracturing or jointing. These roof characteristics were found to differ from mine to mine, with each mine having unique roof conditions.

CONCLUSIONS

The roof bolt pull test was demonstrated in this investigation to be an effective means for testing resin-grouted bolt installations for load-carrying capabilities in evaporite minerals. Such data can be assembled to provide information on bolt integrity from the standpoint of the ability to resist axial loads, the practical limit being the yield strength of the steel rebar.

Another outcome of this investigation indicates that the ECL can be an essential parameter in evaluating a bolt's ability to take loads at different column lengths. The ECL procedure was demonstrated as a practical approach to the formulation of a column length criterion for resin bolts. Although the ECL determinations are site specific, they do provide general baseline data regarding the competency of bolt installations where shortened columns occur.

Unit anchorage can be useful, particularly at lesser column lengths, as an index measurement of the grout-to-rock contact, provided the axial loading is small with minor steel deformation allowed in the resin bolt system and also assuming that the rock is weaker in strength than the resin. In this way, failure of the steel-grout interface can be minimized. Differences in unit anchorages illustrate the varying bond characteristics that occur from hole to hole as a result of changing borehole conditions due to differences in hole size and in physical and lithologic features.

This study suggests that the best approach to developing a resin-grouted bolt criterion for a mine is to address the specific roof conditions rather than to rely on less pertinent empirical data taken from other mine sites.

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APPENDIX A.--BOLT EFFECTIVENESS AND PULL-TEST RESULTS FOR DIFFERENT COLUMN LENGTHS IN ALL MINES STUDIED

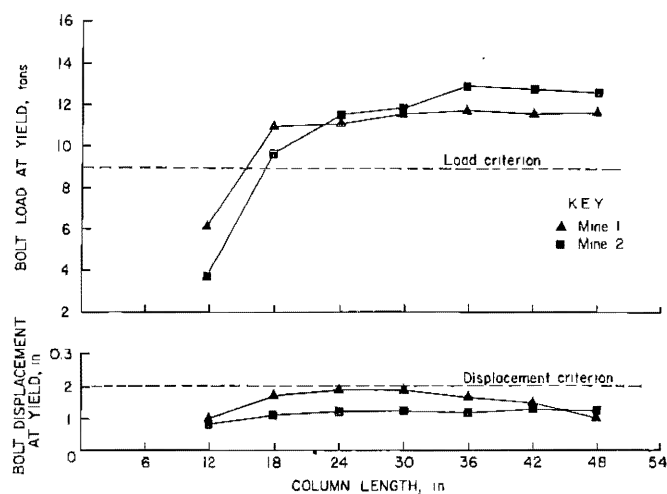


FIGURE A-1.—Pull-test results for salt mines.

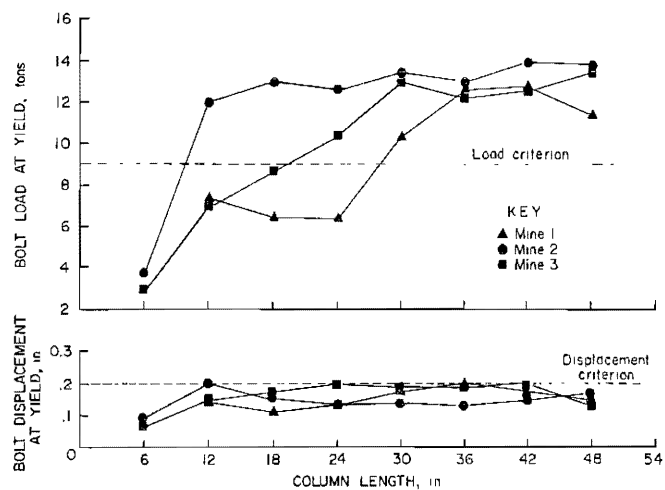


FIGURE A-2.—Pull-test results for potash mines.

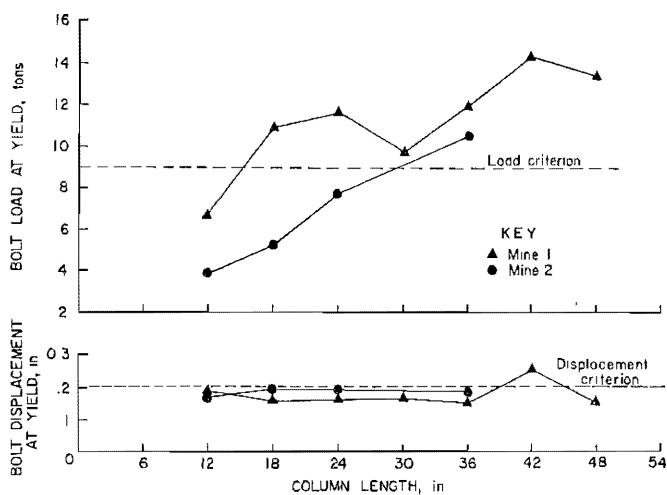


FIGURE A-3.—Pull-test results for gypsum mines.

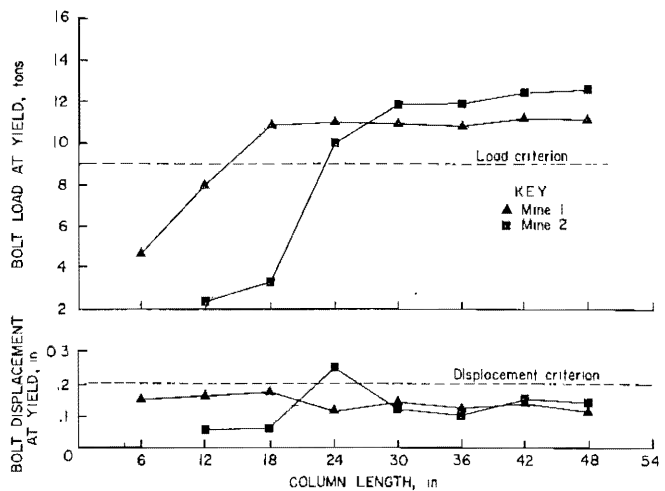


FIGURE A-4.—Pull-test results for trona mines.

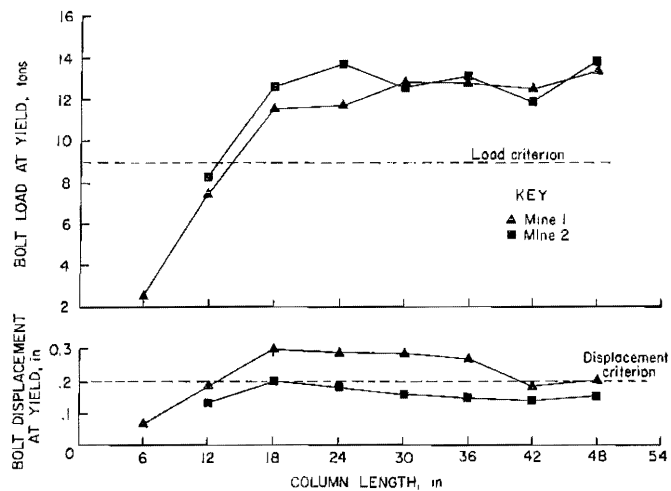


FIGURE A-5.—Pull-test results for borate mines.

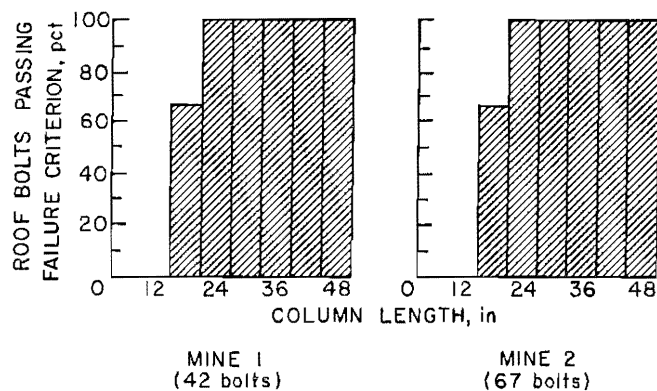


FIGURE A-6.—Bolt effectiveness in salt mines.

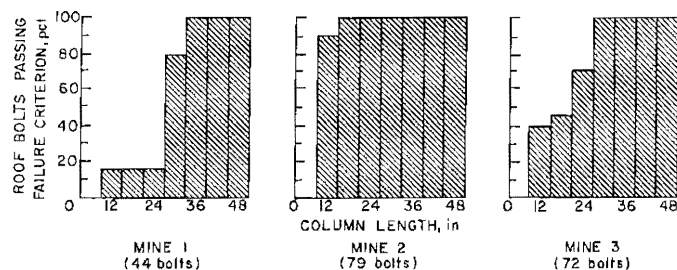


FIGURE A-7.—Bolt effectiveness in potash mines.

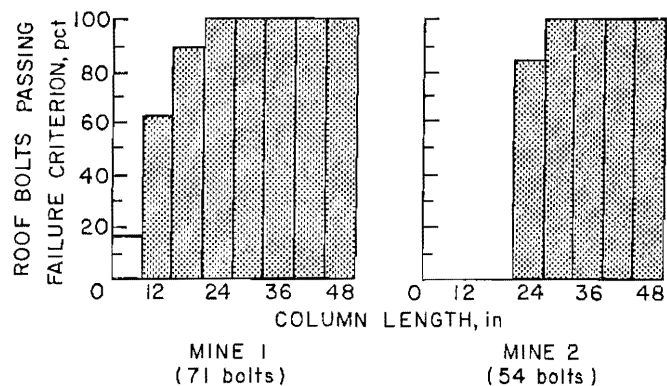


FIGURE A-8.—Bolt effectiveness in gypsum mines.

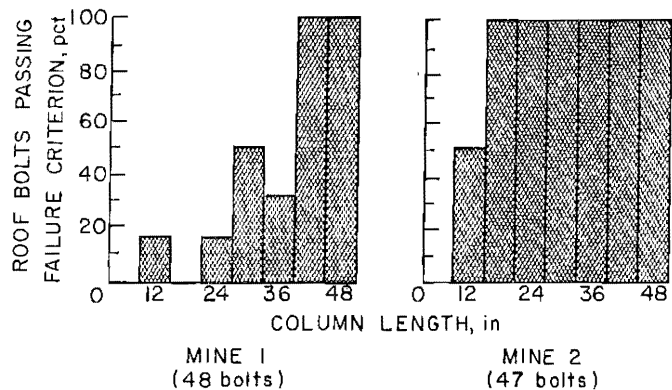


FIGURE A-9.—Bolt effectiveness in trona mines.

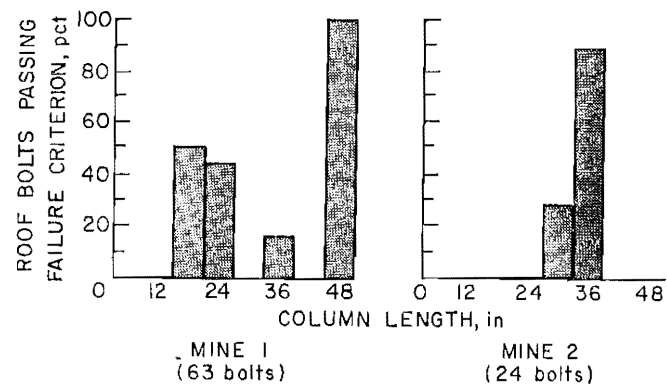


FIGURE A-10.—Bolt effectiveness in borate mines.

APPENDIX B.--BACKGROUND GEOLOGY OF STUDY SITES

SALT

The two salt study sites occur in two distinct types of salt deposits, bedded and domal. While the chemical compositions are the same, the regional geologies are not.

One test site, characterized as bedded, occurs in the Salina Formation of northern Ohio at a depth of approximately 1,600 ft. This formation consists of four major salt zones totaling nearly 200 ft thick interbedded with dolomite, anhydrite, and shale (11).¹

The other site is contained within a salt dome in southern Louisiana. The dome is best described as having isoclinal folding and is roughly circular in plan and approximately 2.5 miles in diameter. The domal salt is remarkable pure (96 pct NaCl) with minor inclusions of anhydrite and shale. However, the intense folding sometimes leads to roof slabbing in some mine locations (2).

POTASH

All three potash study sites are contained within the Carlsbad district of southwestern New Mexico. Massive beds of potash consisting of 12 separate horizons averaging 4 ft in thickness are located within the Permian-age Salado Formation (8). The minable potash beds are bounded by thick halite deposits. In general, the richest potash minerals occur in the younger upper portions of the Salado (15). The minable potash seams include sylvenite and langbeinite (10 to 22 pct K₂O) (8). Mine depths range from 1,000 to 1,650 ft. Shale and clay partings represent potential boundaries for roof falls.

TRONA

Both trona study sites lie in the trona mining district of southwest Wyoming. The trona beds, ranging from a few

inches to over 38 ft thick, are primarily contained within the Wilkins Peak Member of the Green River Formation. The U.S. Geological Survey has studied the trona deposits in the Wilkins Peak Member, numbering the 25 principal beds in ascending order (7). The strata between trona beds often consist of oil shale and green marlstone. The minable trona for both study sites is located within the 17th and 24th trona beds, in different geologic horizons at depths of 800 and 1,500 ft respectively. Bed thicknesses average 10 to 15 ft at the two sites. The roof rock contains alternating beds of soft green marlstone between layers of trona. Bed separations often occur along the trona-marlstone boundaries owing to the differential hardnesses of the two materials.

GYPSUM

The two gypsum test sites are located in different geologic horizons. They are the Permian-age Blue Rapids gypsum in northeastern Kansas and the Mississippian-age shoals deposits located in the St. Louis Formation in southeastern Indiana.

The deposit near Blue Rapids consists of a massive white gypsum bed, 8 to 9 ft thick and 80 ft deep, which underlies the Easley Creek Shale and overlies the Bader Limestone (14). The Shoals gypsum bed lies 350 to 550 ft below surface and is 14 to 16 ft thick. It underlies the St. Louis Limestone, which has been subjected to solution erosion along bedding and joint planes, causing an extensive network of water-filled cavities (1). Water flooding is a problem during mining and requires careful hydrological studies.

BORATE

The two borate test sites investigated in this study are located in southeastern California. The lenticular-shaped deposits from both test sites are believed to have been precipitated in a shallow basin fed from nearby thermal springs containing enormous amounts of sodium and

¹Underlined numbers in parentheses refer to items in the list of references preceding appendix A.

boron dispersed within a lacustrine sequence of mudstone, shale, and sandstone (12). Eventual remineralization due to ground water percolation accounts for much of the different facies observed in borate. The primary suite of borate minerals includes colemanite, ulexite, probertite, and borax. Prevalent characteristics observed in the ore at both mines include zones with microfaults,

brecciation, fractures, convoluted bedding, and limestone and gypsiferous laminations (16). These features are important considerations when addressing roof stability in underground borate mines. The depths of the ore at both sites range from 300 to 1,00 ft below surface. The mine sites are located in different geologic horizons.